

# Energy needs and vulnerability estimation at an urban scale for residential neighbourhoods heating in Madrid (Spain)

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*ABSTRACT: Urban areas renovation may lead to problematic situations associated with financing of the works in absence of a detailed analysis of the distribution of resources. An analysis of the needs and the obstacles in achieving buildings refurbishment to improve their energy efficiency must be observed. Buildings requiring energy refurbishment will be those with poor construction quality, not adapted to the new energy efficiency requirements. People with insufficient resources to deal with such actions will inhabit many of them. This paper proposes a model for energy needs assessment at an urban scale with the objective set on the refurbishment of residential buildings neighbourhoods, addressing comfort needs. In this sense, aspects of building energy vulnerability are explored as a prerequisite to the analysis of energy poverty in our cities and neighbourhoods. A methodology to characterize heating needs of urban areas is developed by using statistical data from the Spanish Census of Housing and Population. The superimposition of resulting demand values with demographic data allows introducing socio-economic criteria in order to locate urban energy efficiency and fuel vulnerability. This information is useful in order to address specific public refurbishment strategies based on the reality of socioeconomic aspects of the neighbourhoods and the state of preservation of buildings.*

*Keywords: fuel poverty, energy needs, urban refurbishment*

## INTRODUCTION

Energy poverty, one of the adverse social impacts of inefficient domestic energy consumption (Healey and Clinch, 2002), is the outcome of the combination of three household-scale factors: family income, energy prices and the energy efficiency of the home.

As a rule, whilst older and lower quality housing requires the most intensive refurbishment, it also tends to be occupied by people with insufficient means to undertake the action needed. The result is that higher energy costs per person and unit of net room area for befall the most vulnerable segment of the population (Santamouris et al., 2007). In such cases, energy efficiency is not the only objective: general building maintenance would itself justify the measures required.

In Spain, further to European ENTRANZE project data for 2008, 83 % of all dwellings are occupied by their owners, 86 % of whom have low incomes and 12.6 % are over the age of 65. Consequently, refurbishment goals set without a detailed study of the distribution of resources in the urban area where intervention is planned may be thwarted by a lack of funding.

Specific political proposals involving public investment in energy refurbishment have been put forward. Such proposals should be based on clear

principles of equity and envisage building regeneration in areas inhabited by vulnerable segments of the population under premises of energy efficiency and comfort.

One of the major problems in persuading the general public of the benefits of improving the energy efficiency of buildings lies in explaining what the conceit means. Efficiency is the ratio between the energy required to reach and maintain a comfortable indoor environment (demand) and the amount of fuel needed to do so (consumption). These two factors depend on the local climate, building orientation and shape factor (area exposed per volume), the construction elements that bound the space to be conditioned, the type of fuel and the generating devices that convert it to heating or cooling.

The tool developed in this study is designed to facilitate communication between the authorities and the public at large and educate the latter in connection with energy efficiency in urban buildings. Cities such as Copenhagen have a protocol in place to reach CO<sub>2</sub> neutrality (City of Copenhagen, 2009) and some authors have proposed ways to map energy poverty (Morrison and Short, 2008) based on social indicators of deprivation. Graphics showing whole cities' energy behavior have not been forthcoming, however. This

study proposes a first-ever graphic overview of the heating energy demand in an entire city, quarter-by-quarter. A diagnosis is provided of the city as a whole as an energy-dissipating entity and the areas where the building stock is least efficient are identified.

## OBJECTIVES

Planning, i.e., preliminary investment in socio-economic and zoning studies to define public investment targets is requisite to implementing refurbishment policy.

The general aim of this study is to apply robust statistical data to identify urban areas hosting a vulnerable population whose dwellings afford inefficient heating.

Its specific objectives include obtaining:

- an estimate of the order of magnitude of heating energy demand in urban areas
- a thermal quality indicator for the residential buildings in each city quarter with which to identify energy inefficiency pockets in need of reform.

## METHODOLOGY

The first step in the procedure followed in this study was to determine the total number of dwellings and estimate the total area to be heated in each quarter. The data analyzed were drawn from Spain's population and housing census (National Statistics Institute, INE, 2001), a snapshot of the population obtained from a survey conducted in 2001. Since respondents' replies to the questionnaire used, which covered several areas, are protected, the smallest scale to which publicly accessible data are broken down is the census precinct, the statistical units into which Spain is divided.

In the second step, the total area of housing to be heated was classified by date of building construction, thereby identifying the legislation on heating applicable to each group.

Unit heating demand was determined for each construction period with energy simulation techniques. Total heating energy needs by census precinct were estimated in both absolute values and energy density by area (Ha) by attributing the characteristic values for each construction period to the total indoor area to be heated.

Dividing the total demand values calculated by the area in square meters to be heated in each census precinct, energy categories were found for each quarter and the city as a whole further to the energy efficiency scale for Madrid's climate computed as specified in the legislation (IDAE, 2011).

Vulnerable quarters that also host the city's lowest energy efficiency buildings were identified by cross-referencing the results with the city of Madrid's Urban Vulnerability Atlas (Hernández Aja et al., 2011).

## GENERAL ASSUMPTIONS

Urban vulnerability, in conjunction with energy efficiency shortcomings in existing buildings and other factors, was assumed to be a determinant of energy poverty.

A building's energy demand was assumed to be a suitable indicator for quantifying building-related energy vulnerability, for it determines the energy needed to establish indoor thermal comfort and depends largely on geometric and construction characteristics.

The assumption adopted to characterize the residential heating energy demand by construction period in Madrid's climate was that such demand depends more on envelope performance in terms of insulation than on other considerations such as building orientation or shape factor which, while not negligible, have a lower impact. Similarly, buildings' thermal characteristics (defined by the period when they were erected) were assumed to be related to the range of their heating energy demand.

## HOUSING IN MADRID

Statistical data show that housing in Madrid consists in multi-dwelling units. In 2001, 46 953 or just 4 % of its total housing stock of 1 080 306 primary residences were single family homes (INE, 2001). Moreover, nearly 70 % of the city's primary residences were built between 1941 and 1980 (Table 1) and are considered as the most inefficient stock (Oteiza et al 2015).

*Table 1: Distribution of primary residences in Madrid by construction period (INE, 2001)*

TOTAL	Prior to 1900	1901 to 1940	1941 to 1980	1981 to 2001
1 080 364	36 522	92 357	739 639	207 313
100 %	3.38 %	8.55 %	68.46%	19.19 %

The residential built area specified in the population and housing census for a given city can be used to roughly estimate the indoor area to be heated, broken down by census precinct and classified by construction period. The age of Madrid's residential buildings is mapped in Figure 1.

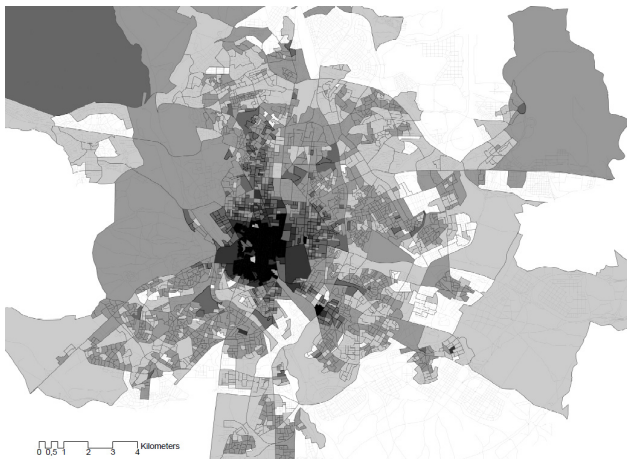


Figure 1: Age of residential buildings in Madrid

In addition to building age, which largely determines wintertime energy needs, housing density should be analyzed to estimate the order of magnitude of the total demand for a given part (one or more census precincts, quarters or districts) of the city and with it the infrastructures required to ensure supply. Figure 2 shows building density in Madrid.



Figure 2: Housing density in Madrid

### HEATING DEMAND INDICATOR

A two-step procedure was designed to define an indicator able to roughly characterize heating demand and classify housing in Madrid by demand category. First, the official procedure set out in the legislation was deployed to find the upper and lower limits of each class on the energy efficiency scale for the item 'heating demand'. The values found for the scale were then verified by calculating the categories for buildings representative of Madrid's housing stock.

### Energy efficiency certificate scale

The reference heating demand for Madrid (in kWh/m<sup>2</sup> year) (Table 2) estimated by Spain's Energy Diversification and Savings Institute using the official procedure for establishing energy categories (IDAE, 2007 and 2011) was taken as the starting point to determine the energy efficiency scale for heating demand in existing buildings. These values were used to calculate the heating demand category scale.

Table 2: Main reference energy demand for de novo and existing buildings in kWh/m<sup>2</sup> year (source: IDAE, 2011)

Building type	Single family heating	Aptmnt building heating	SF cooling	ApB cooling	SF DHW	ApB DHW
De novo	64.4	43.2	15.7	10.8	17.7	13.0
Existing	149.8	121.2	26.5	19.1	17.7	13.0

That scale, used throughout the European Union as well as in other regions, consists of seven classes denominated from A to G (Table 3). Here, the limits for classes A to D were defined in terms of standardized energy coefficient C1 as set out in Spanish Royal Decree 47/2007 of 19 January on Energy Efficiency Certificates for New Buildings, whilst for categories E, F and G the limits applied were found applying a second coefficient, C2 (IDAE, 2011).

Table 3: Energy efficiency scale for heating demand in multi-unit housing in Madrid

Class	C1	C2	Reference demand	Class ceiling (kwh/m <sup>2</sup> year)
A	0.15		43.2	9.40
B	0.5		43.2	21.85
C	1		43.2	39.64
D	1.75		43.2	66.32
E		1	121.2	121.20
F		1.5	121.2	132.22
G			121.2	≥132.22

This energy indicator was used to compare residential heating energy demand in the city's various quarters.

Other energy indicators (also yearly and per unit of net room area) that could be used for a thorough analysis of all energy-based residential building services include:

- Energy demanded by the building for other energy-significant services (in housing: cooling and domestic hot water).
- Breakdown of primary energy consumption by energy-significant building service.

- Breakdown of CO<sub>2</sub> emissions by energy-significant building service.

### Simulation of representative buildings

The heating energy demand scale was adjusted on the grounds of the simulations conducted for housing representative of the building stock. Buildings were classified by construction period and the thermal transmittance requirements for building envelopes in place at the time of construction were used to calculate heating demand for each period. All buildings erected prior to 1979 were assumed to lack thermal insulation (Oteiza et al 2015). The usage parameters for all existing buildings were assumed to be as set out in Spanish energy efficiency regulations (CTE, 2013) and the ventilation rate to be one air change per hour.

Table 4: Standard buildings in Madrid: real and simulated (yellow highlighting) heating demand by construction period

BUILDING TYPE	<1979	1979-2006	HE* 2006	HE 2013
1 Semi-detached, single family, 1990s Grnd+1, standard quality	122.89	79.13	71.61	40.00
2 Detached, single family, 1940s Grnd+2, high quality	109.90	87.50	72.82	40.00
3 Multi-dwelling (1), 1960s Grnd+3, low quality	147.77	97.23	79.11	52.00
4 Multi-dwelling (2), 1960s Grnd+4, medium-low quality	115.00	85.66	58.26	52.00
5 Multi-dwelling in closed city block Grnd+4, structural walls <1900	116.53	78.26	72.54	52.00
Range	109-148	78-97	58-79	40-52
Mean	122.42	85.56	70.87	47.2
Percentage of 1979 mean	100%	70%	58%	39%

\*HE: code name for energy savings specifications, one of the 'basic documents' that form part of Spain's Technical Building Code

The yellow highlighting denotes demand calculated for real existing buildings; the value in the same row in column is the result of a simulation for the same building assuming other construction period's characteristics; the values in columns 3 and 4 are the maximum allowable in HE 2006 and HE 2013, respectively, for each building.

Buildings with no insulation exhibited a wider range of heating demand values. The factors determining variability were compactness, orientation, shade from nearby elements and construction quality. These findings suggested that the impact of such factors declines with rising thermal insulation in the building envelope. Consequently, the simplification entailed in grouping all buildings erected before the entry into effect of the 1979 Building Code under the same heading was consequently deemed acceptable for the purposes of this study.

### Heating demand indicators by period

The efficiency values found for buildings built prior to 1979 were observed to range widely (from 109 to 148 kWh/m<sup>2</sup> year). With a view to harmonizing those findings with the energy category scale for residential buildings in effect in Spain, all pre-1979 buildings were arbitrarily assigned the maximum value on the scale (132.22 kWh/m<sup>2</sup>/year) (see Tables 3 and 4).

That value was then used to estimate values for each period on the grounds of the mean heating demand reduction found with the energy simulation exercise.

Table 5: Heating demand by period (kWh/m<sup>2</sup> year)

<1979	1979-2006	>2006	CTE* 2013
132.22	92.41	76.54	52

\*CTE: Technical Building Code in effect in Spain

## RESULTS

The methodology proposed delivered an estimate of the order of magnitude of the energy demand that would ensure a comfortable indoor environment in Madrid's housing during a typical winter. Further to that estimate, in 2001 it took approximately 10 750 000 MW (924 333 ktoe) of thermal energy per year to heat residential buildings in the city of Madrid to the comfortable temperature defined in the existing regulations.

These findings were used to map the heating needs in Madrid as a whole and broken down by the criteria described below.

### Heating energy demand per hectare

The energy demand per hectare found from the energy demand estimates identified the geographic areas with highest energy demand density. This indicator is associated with housing density and area in each quarter and the period when its buildings were erected, which determines the energy quality of the enclosures (Fig 3).

### Heating demand by census precinct

The demand data were likewise used to determine the thermal quality of the housing in a given census precinct in terms of its heating energy demand. Applying the values obtained for each precinct to the area of the buildings within its bounds yielded mean energy demand per unit of area and year for each census precinct (kWh/m<sup>2</sup>/year).

Geographic information system (GIS) software was used to map all the census precincts within the Madrid city limits with their heating demand-based energy category as calculated with the procedure laid down for existing residential buildings in the legislation in effect (IDAE, 2013) (Fig. 4).



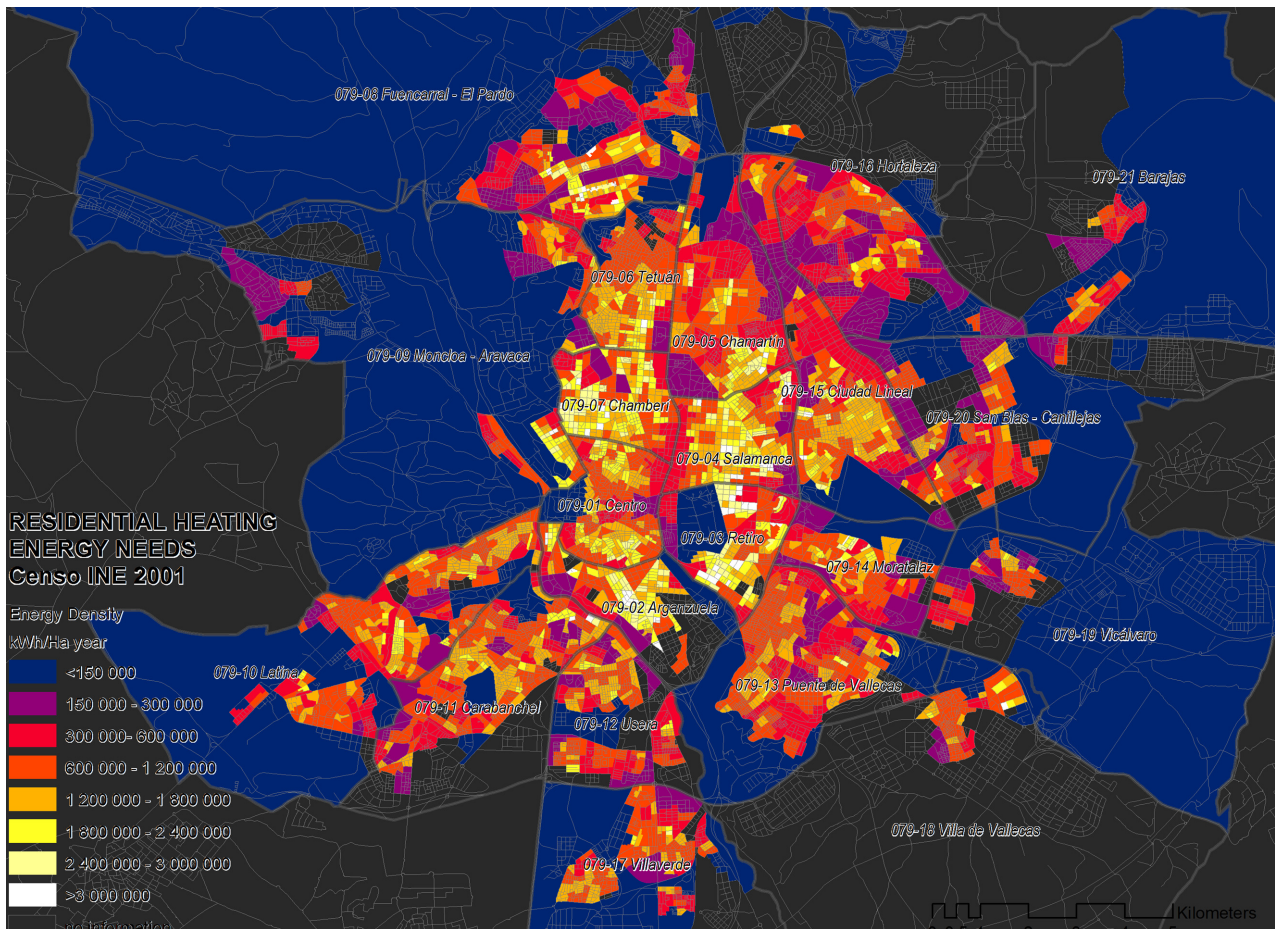


Fig.3: Heating demand density (MWh/Ha year)

With the methodology proposed, the mean heating demand found for the city of Madrid was 123.65 kWh/m<sup>2</sup> per year, according to which the city as a whole would be energy demand-rated as class F. That value closely resembles the IDAE figure for existing buildings in Madrid's climate (Table 2).

#### Energy inefficiency in vulnerable quarters

The city's vulnerable quarters that also host inefficient residential buildings were identified (Fig. 5) by cross-referencing the energy category obtained for each area of the city with Urban Vulnerability Atlas data (Hernández Aja et al., 2009-2011).

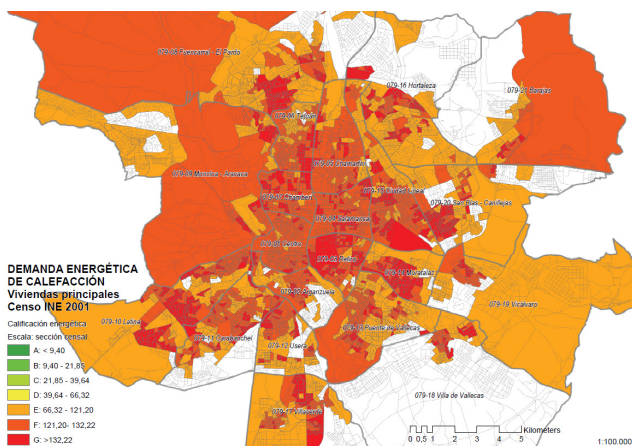


Fig. 4: Energy category in Madrid by quarters (kWh/m2 year)

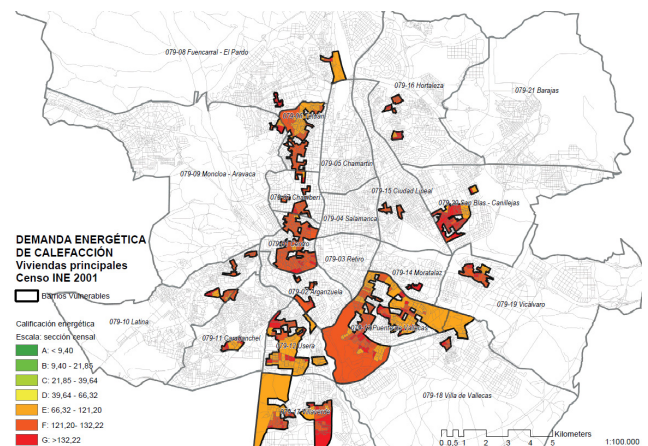


Fig. 5: Energy categories in vulnerable quarters

## CONCLUSIONS

Based on the city of Madrid's thermal energy needs to ensure a comfortable indoor wintertime environment in all its housing (924 333 ktoe or 10 752 274 MWh), its residential heating demand (with a mean kilowatt-hour per square meter and year of 123.65 kWh/m<sup>2</sup>) would be rated as class F. If building refurbishment could raise that category to class D (maximum 66.32 kWh/m<sup>2</sup> year) as required by the country's Technical Building Code, the city's energy demand could be lowered by approximately 46%. That would enhance comfort and reduce energy consumption and pollutant emissions substantially, with the concomitant improvement in the quality of urban air. Under that assumption, 495 918 ktoe (5 767 530 MWh) of thermal energy would be required for comfortable indoor residential conditions.

No direct relationship was found between the quarters classified as vulnerable and the energy efficiency of the respective residential buildings, inasmuch as different levels of thermal quality were observed for the buildings in those quarters.

Areas on the outskirts where urban vulnerability was observed to concur with buildings with high energy demands may be at risk of energy poverty. Housing construction in those areas is of a lower quality and its inhabitants will find it difficult to fund the reforms needed to enhance energy efficiency.

## ACKNOWLEDGEMENTS

The present study was conducted at Departamento de Urbanística y Ordenación del Territorio from Polytechnic University of Madrid and the Eduardo Torroja Institute for Construction Science and funded under Spanish Ministry of Economy and Competitiveness REFAVIV project number BIA-2012-39020-C02-01.

## REFERENCES

- Agustín Hernández Aja, Mariano Vázquez Espí, Carolina García Madruga, Ángela Matesanz Parellada, Elena Moreno García, Julio Alguacil Gómez, Javier Camacho Gutiérrez. 2009-2011. *Análisis urbanístico de Barrios Vulnerables de 1991 y 2001*. Madrid (España).
- Healey, J. D., y J. P. Clinch. *Fuel poverty, thermal comfort and occupancy: results of a national household-survey in Ireland*. Applied Energy (Elsevier), nº 73 (2002): 329–343.
- Colin Morrison, Niamh Shortt. *Fuel poverty in Scotland: Refining spatial resolution in the Scottish Fuel Poverty Indicator using a GIS-based multiple risk index*. Health & Place 14 (2008) 702–717
- Fernández Boneta, M. (2014). *Policy scenarios and recommendations on nZEB, deep renovation and RES-H/C diffusion: the case of Spain*. ENTRANZE Project. National Renewable Energy Centre (CENER), Spain.
- Ferrante, A. (2014). *Energy retrofit to nearly zero and socio-oriented urban environments in the Mediterranean climate*. Sustainable Cities and Society 13 (2014) 237–253
- I. Oteiza, C. Alonso, F. Martín-Consuegra, J. Monjo, M. Gonzalez-Moya. *Energy retrofitting for social housing by improving the building envelope: Madrid 1939-79*. The sustainable renovation of buildings and neighbourhoods. Ed. P. Mercader-Moyano. Bentham Science Publishers. 2015. eISBN 978-1-68108-064-2, ISBN 978-1-68108-065-9.
- Santamouris, M., K. Kapsis, D. Korres, I. Livada, C. Pavlou, y M. N. Assimakopoulos. *On the relation between the energy and social characteristics of the residential sector*. Energy and Buildings (Elsevier), nº 39 (2007): 893-905.
- City of Copenhagen. (2009). *Copenhagen climate plan*. 1599 Copenhagen V: The Technical and Environmental Administration, City Hall.
- IDAE 2007. *Escala de Calificación Energética para Edificios de Nueva Construcción*
- IDAE 2011. *Escala de calificación energética para edificios existentes. Calificación de Eficiencia Energética de Edificios*.
- ENTRANZE. *Policies to enforce the transition to nearly Zero Energy Buildings in the EU-28*. Co-funded by the Intelligent Energy Europe. Programme of the European Union Grant agreement no. IEE/11/922/SI2.615942.
- España, Real Decreto 47/2007, de 19 de enero, por el que se aprueba el procedimiento básico para la Certificación de Eficiencia Energética de Edificios de Nueva Construcción
- España, *Norma Básica de la Edificación sobre Condiciones Térmicas de los Edificios*. Boletín Oficial del Estado (BOE) del 22 de octubre 1979.
- España, *Código Técnico de la Edificación. Documento Básico HE Ahorro de Energía*. Versión publicada en el Boletín Oficial del Estado (BOE) del 12 de septiembre 2013 con corrección de errores del BOE del 8 de noviembre de 2013.